Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
Proceedings IAU Symposium No. 340, 2018
D. Banerjee, J. Jiang, K. Kusano & S. Solanki, eds.

doi:10.1017/S1743921318001862

Evolution of structures with an open magnetic flux over a hundred years

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Abstract. Reconstruction of regions with an open configuration of magnetic force lines was carried out according to synoptic H_α maps over a period of more than 100 years. It is shown that the maximum area of open structures in the cycle of solar activity is reached in the descending phase, $1 \div 2$ years before the onset of the minimum. The total area of open structures in the current cycle n has a high correlation ($r \sim 0.8$) with the amplitude of the next activity cycle $n+1$. There is also a secular envelope with a maximum in the middle of the 20th century.

Keywords. Sun, solar activity, long-term variations

1. Introduction

The "open" magnetic flux is part of the solar magnetic field, which extends into the heliosphere and becomes an interplanetary magnetic field (IMF). Open fields play an important role in heliophysics as the main factor of geomagnetic activity.

Historical observations of geomagnetic activity can be used to identify long-term variations in the open flow and solar wind parameters on the Earth's orbit, such as the intensity of the interplanetary magnetic field and the speed of the solar wind Lockwood (2013). Lockwood *et al.* (1999), the authors used the *aa* index to reconstruct an open magnetic flux and concluded that the magnetic flux F_s doubled in the period 1900-1950.

Based on IDV index Svalgaard and Cliver (2005) concluded that the intensity of the magnetic field B in the period 1900-1950 increased by only 25%.

Long-term reconstructions of geomagnetic activity use longer periods of sunspot activity. These reconstructions are based on the close behavior of geomagnetic indices and sunspots in 100-year cycles, with a sufficiently large time averaging longer than the duration of the 11-year activity cycles. However, the key difference between the variation of sunspots and the values of geomagnetic indices (for example, aa) is that the sunspot activity indices in the activity minima tend to zero, while the geomagnetic indices have a long-term trend.

An attempt to simulate an open flow based on sunspot data of RGO gives rather poor results. The simulated open flow is shifted back in time, and the open flow minima are too low compared to the recovered IMF values. Some improvement is achieved when we add the contribution of the open flow to the ephemeral regions and the magnetic flux to the sun in the chromospheric network Krivova and Solanki (2004) or the flux transfer as a result of surface transport Cameron *et al.* (2010). However, there is still no sure answer to the question of which mechanism can be responsible for the accumulation of a magnetic field for more than 11 years.

At the same time, the knowledge of the magnetic field over the Sun's disk is necessary for the modeling of magnetic fields, and reliable magnetographic observations began after

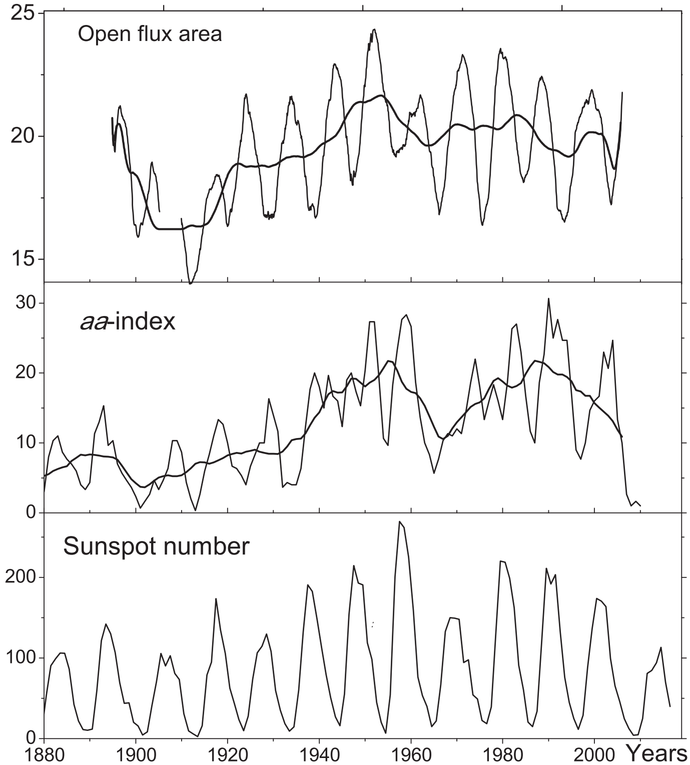

Figure 1. The total area occupied by open flux in % of the solar surface, reconstructed from the synoptic H_α maps (top panel) in comparison with the *aa*-index (middle panel) and the sunspot activity index.

1975, and consequently after the growth of geomagnetic indices in the period 1900-1950. Therefore, the question of the cause of long-term trends in geomagnetic indices remains open.

2. Data

The interplanetary magnetic field is mainly produced in coronal holes (CH), which are regions with an open magnetic field on the Sun. The solar wind, consisting of electro-conductive plasma of these areas extends in the magnetic field lines heliosphere. During of the sunspot minimum, the open magnetic flux has its origin from the polar regions, while during the maximum activity cycle, CH forms at low latitudes, having a relatively small area but with a high magnetic field strength. Wang *et al.* (2000) extrapolated the NSO / KP magnetographic observation data to the source surface and found that the open flow lags 1-2 years from the sunspot cycle, and its amplitude changes by a factor of 2 with the activity cycle of the spots, unlike the much larger variations (factor $\sim\ 3-4$) of the total solar flux.

Open flow modeling results calculated from the source surface model (PFSS) show that a significant part of the open flow is lost, especially during the sunspot maximum and the growth phase of the new cycle. The PFSS model does not include coronal mass ejections (CME), which carry the magnetic field from the Sun into interplanetary space and are more frequent during the maximum activity. In order to take into account these contributions, it is possible to change the radius of the surface of the source Rss with

https://doi.org/10.1017/S1743921318001862 Published online by Cambridge University Press

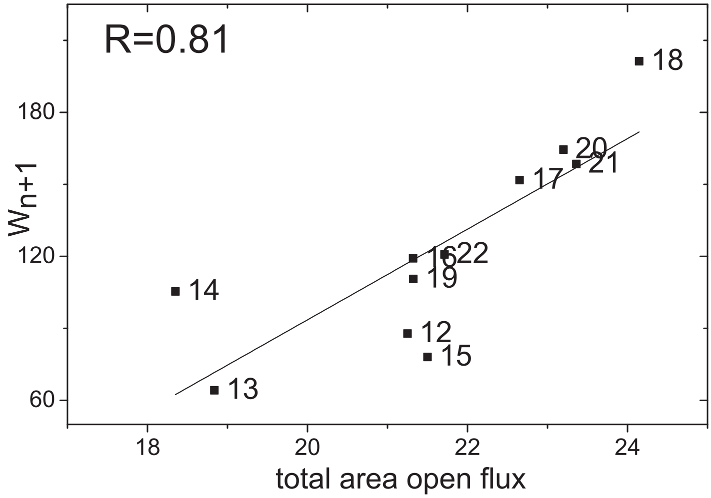

Figure 2. Regression between the amplitude of total area with an open magnetic flux and the amplitude of the next cycle of sunspot activity.

time. At the maximum activity, the surface of the source is considered closer to the photosphere than at the minimum of activity.

In this paper, to explain the long-term trend of geomagnetic indices, we will use data on the polarity of a large-scale magnetic field obtained from observations of the chromosphere in H_α line. These charts show boundaries of magnetic field's polarity. Fixed datums obtained from optical observations were used as tracers. These are observations of filaments, filament channels, solar prominences. Thus, in contrast to magneto graphics observations, the position resolution of which is constantly increasing owing to telescope upgrading, H_α charts contain boundary of spacial resolution of the sphere occupied with this or that magnetic field polarity. These data cover the period 1887-2016. and were reconstructed by various authors: 1887-1915 Vasilieva (1998); 1915-1964 Makarov & Sivaraman (1989); 1964-1979 McIntosh (1979); 1979-2017 - the data of Kislovodsk Tlatov (2009).

The PFSS model is widely used to simulate a global magnetic field in the corona. The photospheric magnetic field in the form of a weather map is given as a boundary condition at the inner boundary $R = 1.0R_o$. The model is based on the assumption that the magnetic field lines become radial on the hypothetical surface of the source at a distance of $R_s = 2.5R_o$ from the center of the Sun. The decomposition into spherical harmonics is carried out on the synoptic map according to the magnetic field data. The search for expansion coefficients was described in Tlatov *et al.* (2016).

The magnetic field on the maps takes the values ± 1 G. To correct the amplitude of the magnetic field intensity with the phase of the activity cycle, we used a factor that depends on the phase of the cycle and the latitude (θ): $10 \cdot abs(phase(t) - 0.5) * sin^2(\theta)$. The cycle phase function as a function of time t was calculated for the cycle n as $phase(t) = (t - T^n_{min}/(T^{n+1}_{min} - T^n_{min})$. To determine the area of structures with an open magnetic flux, we determined the footpoints of magnetic lines of force that descended from the source surface to the photosphere.

As shown in Fig. 1, the total area occupied by open flux are S_{CH} compared with the *aa*-index and the sunspot activity index. On the graph, the data are smoothed out by 27 Carrington rotations. For S_{CH} and *aa*-index, the envelope lines obtained by averaging over the 11-year period is presented.

Area of open flux are decreases from $\sim 20\%$ of the solar surface near sunspot minimum to only $\sim 7\%$ at sunspot maximum. We can note that the maximum area of open structure was maximized before the 19th cycle of activity $\sim 25\%$ in the decay phase of the 18th cycle. In the 13th and 14th cycles of activity, the share of the area of structures with an open magnetic flux was $\sim 18\%$. Between the maximum area of structures with an open magnetic flux in the 11-year cycle and the amplitude of the next cycle of activity Fig. 2 with a correlation $r \sim 0.8$. There is also a long-term trend, which shows growth in the period 1900-1955.

3. Conclusion

In this paper, we estimate the area of structures with an open magnetic flux from the data on the distribution of the polarity of the solar magnetic field, obtained from observations in the H_α line. The total area has 11-year modulation. The amplitude of the 11-year modulations has a significant correlation with the amplitude of the next cycle of sunspots (Fig. 2). This relationship can explain one of the precursor methods Ohl (1976) where the precursor is the geomagnetic activity in the declining phase of the previous cycle. Geomagnetic activity depends on two main components. These are high-speed solar wind flow from coronal holes, as well as the influence of sunspot activity and coronal mass ejections.

Long-term modulation of the total area with an open magnetic flux S_{CH} is close to the long-term variations of geomagnetic indices. In our study, we used data on the distribution of large-scale magnetic field polarity, and did not use data on the intensity of the magnetc fields. Perhaps centennial modulation of geomagnetic activity is associated not only with the total magnetic flux of the Sun F_s, but also with topology of a large-scale magnetic field.

This work was supported by of the RSF N 15-12-20001.

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